Fermi National Accelerator Laboratory

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Charge Collection in a Hybrid Photodetector

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Introduction

The hybrid photo detector (HPD) has been adopted as the CMS hadron calorimeter (HCAL) baseline photon transducer. It consists of a photocathode in close (~2 mm) proximity to a PIN diode. A thin passivation layer on the PIN diode provides an offset to the backside bombardment of the diode by photoelectrons accelerated by the cathode bias voltage - V_C. Since it takes 3.6 eV in Si to liberate an electron-hole pair, the gain of the device is, $G \sim (V_C - V_T)/3.6$, where the passivation threshold voltage is VT. For example, with $V_T = 2$ kV, and $V_C = 10$ kV, the device gain is 2222. Thus the device acts somewhat like a classical PMT, but can operate in the 4T magnetic field of CMS.

Charge Carriers in the PIN Diode

The mobility, μ, of the electrons and the holes is $\mu_n = 1450$ cm^2/Vsec and $\mu_p = 450$ cm^2/Vsec. The Si structure of the HPD PIN diode is shown in Fig. 1. The P layer is highly doped but shallow as is the N+ layer (the "backside"). The main N layer is only lightly doped. The bias voltage for reverse bias is $V_B > 0$. The P and N+ layers provide good ohmic contact to the substrate. The N+ layer also allows for over depleted operation. The electrons liberated in the N layer move to the N+ backside, while the holes move to the P junction. In DC coupled operation, charge is taken off the P side. Basically the device acts like a solid state ionization chamber, except that both charge signs have finite mobility, and the electric field in the N gap is not constant.

Fields and Potentials in the PIN Diode

Assuming that only the N layer has finite thickness, the depletion of the diode junction causes a constant ion charge density ρ in the N layer. Since $\Delta * D = \rho$, the electric field E is linear in x. Since the field is the gradient of the potential V, the potential is quadratic in x. The fields are illustrated in Fig. 2.

$$\begin{aligned} V(x) &= V_B[1 - (x/d)^2] \\ E(x) &= Eo(x/d),\ Eo = 2V_B/d \end{aligned} \tag{1}$$

These expressions apply just at depletion. If the electric field is driven further into the PIN structure, then (see Fig.2) $E(x) = Eo(x+x_d)/d = Eo(x/d) + \Delta E$, $x_d = d(\Delta E/Eo)$. In this over depleted case, there is a finite electric field in all parts of the N layer. Clearly, in this situation the charge collection time will be decreased.

Charge Motion in the N Region

We consider only the simplest case of point illumination. A pair is produced at a single point xo. Note that the range of a 10 kV electron in Si is about 1.4 μm. Therefore, with backside bombardment of photoelectrons accelerated to 10 kV, xo ~ 0 is a reasonable approximation. Note that the thickness of the N layer is d = 300 μm, so that xo/d <<1.

In the approximation that the mobility is independent of the electric field, the velocity is dx/dt = μE. The boundary condition is that x (t=0) = xo. The electrons are swept to x = 0 by the electric field in the N region. Using Eq. 1 for the field, E(x), the solution for x(t) is

$$x_-(t) = xo*\exp(-t/\tau_-),\ \tau_- = d/(\mu Eo) \qquad (2)$$

Therefore, the solution for very large t is that x → 0. The reason is that, just at depletion, the field at x=0 is zero. Hence it takes a very long time to sweep up the electrons. If the PIN structure is over depletion, as in Fig. 2, then the solution for x(t) becomes

$$x_-(t) = (xo + x_d)*\exp(-t/\tau_-) - x_d \qquad (3)$$

As before, x(0) = xo, but the time to arrive at x = o is not finite and = t_d.

$$x_d/(xo + x_d) = \exp(-t_d/\tau_-) \qquad (4)$$

The holes are swept to the P side and arrive at x = d. The electric field increases during this motion, with the corresponding solution.

$$x_+(t) = xo*\exp(t/\tau_+) \qquad (5)$$

The drift time for the holes is defined by the x=d condition, (d/xo) = $\exp(t_d/\tau_+)$. Note that there are 2 time constants, τ_+ and τ_- for the motion of the 2 charge carriers.

Charge Induced on the Electrodes

The motion of the charges in the N region induces charge on the electrodes which is then detected. It is easiest, perhaps, to view the situation from the energy aspect. The charge motion in the field causes work to be done on the charge, thus changing the charge on the electrodes, Q. The PIN diode as a capacitor has energy U, capacitance C.

$$U = CV^2/2 = Q^2/2C \qquad (6)$$
$$dU = qEdx = (Q/C)dQ = VdQ$$

In Eq. 6, q refers to the charge in the N region, E the field there, and Q the electrode charge. Note that the polarity of the charge induced is the same for electrons as holes, since the charge q differs but also the drift direction dx. Consider the electrons first, q=-e.

Using Eq. 1 for E(x), assigning $V = V_B$, and relating dx to dt by the definition of mobility, the expression for the electrode current due to electron motion, $I_-(t)$ is

$$\begin{aligned} I_-(t) &= dQ_-(t)/dt \\ &= -(xo/d)^2(2e/\tau)*\exp(-2t/\tau_-) \end{aligned} \tag{7}$$

The maximum electron current occurs at t=0, when the charge motion is most rapid. Integrating Eq. 7 once and applying the boundary condition that $Q_-(0)=0$ one finds

$$Q_-(t) = -e(xo/d)^2[1 - \exp(-2t/\tau_-)] \tag{8}$$

Note that Q_- at long times reaches the asymptotic value, $-e(xo/d)^2$. Since xo/d is rather small, the electrons contribute little to the charge collection in this device. The basic quadratic behavior of I and Q arises since dQ ~ Edx ~ xdx (Eq. 6). The motion of the holes is always accelerated. Using Eq. 6 and the $x_+(t)$ solutions previously derived

$$I_+(t) = -(xo/d)^2(2e/\tau_+)*\exp(2t/\tau_+) \tag{9}$$

In the case of the holes, the minimum current occurs at t = 0, while the maximum occurs at x = d, which happens at time $t = t_d$, $I_+(t_d) = (2e/\tau_+)$. Integrating the hole current to get the hole charge, with the boundary condition that Q = 0 at t = 0.

$$\begin{aligned} Q_+(t) &= -e(xo/d)^2[1 - \exp(2t/\tau_+) \\ Q_+(t_d) &= -e(xo/d)^2[1 -(d/xo)2) \\ &\sim e \end{aligned} \tag{10}$$

In summary, it is expected that the electron current is small, since backside illumination implies that the charge production point is very near the N+ electrode sink for the electrons. The hole current is expected to rise from a small value to a maximum at $t = t_d$. The charge collected from electrons is small, while essentially all the hole charge is collected in a time t_d. Numerically, for V_B = 100V, d = 300 μm, τ_- = 3.1 nsec and τ_+ =9.9 nsec. Then one finds that t_d = 53 nsec if xo = 1.4 μm. That time is a little long for LHC applications where the bunch crossing time is 25 nsec. For 1 pe released at the cathode, we get 2222 pairs made at xo. The maximum current is then 71 nA which occurs at $t = t_d$.

References

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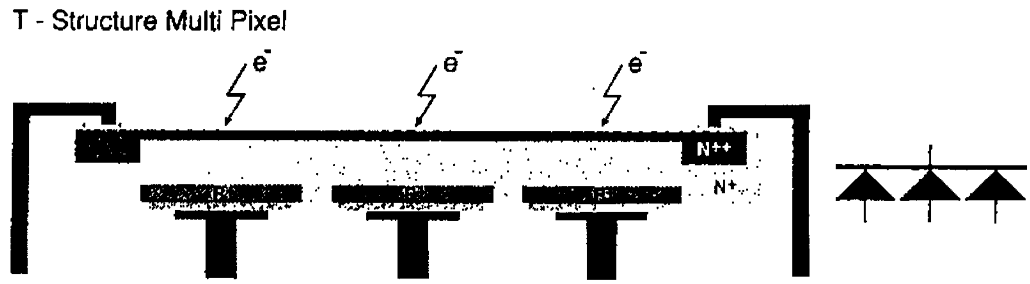
2. G. Lutz and A.S. Schwarz, Ann. Rev. Nucl. Part. Sci (295) 45, 1995

Fig. 1: The Si electrode structure of the DEP HPD. The signal electrode is DC coupled for high rate operation. V_B is the PIN diode ;bias voltage. V_C is the photocathode bias voltage.

Fig. 2: The x dependence of the silicon structure, the electric field just at depletion and over depleted, and the bias voltage.



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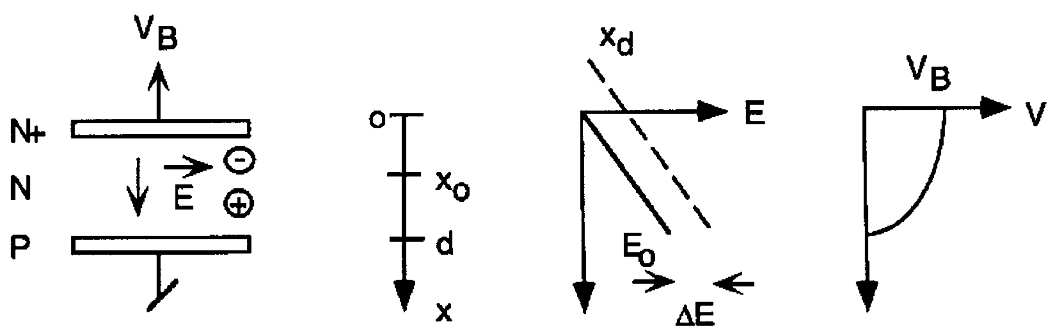

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